Heavy Ion Linear Accelerator in the NUMATRON Project

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1. General Description

NUMATRON is a high-energy heavy-ion accelerator which accelerates the heavy ion such as uranium up to an energy around 1 ∿ 2 GeV/nucleon [1]. It was proposed in 1977 as a future project at INS and since then the preparatory studies have been performed on the many accelerator subjects. The main purpose of the project is a high energy nuclear physics but researchers in various scientific fields will be involved in the project. The design objectives for the injector linac of the main accelerator, which consists of cascade synchrotrons, specify the beam energy of 10 MeV/u and the kinds of accelerated particle of α to uranium with an enough intensity not only to fulfil the synchrotron but also to provide the beam to the related scientific studies such as atomic physics, solid state physics, irradiation experiments and so on. The operation mode of the linac would be a repetition rate of 40 Hz and the pulse width of 300 μs as a synchrotron injector. However, the linac should provide a beam also to the other various facilities and the duty factor of the operation is designed to be 25 % for the heaviest ion such as uranium and cw (continuous wave) for the light heavy ions.

The linac is exclusively an integrated complex because the injection energy to the linac is around 15 Kev (β = 0.57 %) due to the small charge to mass ratio of the extracted beam from the PIG type ion source. Here the terminal voltage of the Cockcroft-Walton pre-accelerator is designed at 500 KV. The low velocity section of the linac should be envisaged carefully and studied experimentally for the good beam acceleration. Another reason for the complexity of the heavy ion linac is the necessity of charge stripping between the linac tanks for the efficient acceleration. In the present design three stripper sections are provided at each specific energies of 300 Kev/u, 1.6 Mev/u and 10 Mev/u. In the paper, results of design and experiments of the low velocity linac are described.

2. Wideröe Type Structure

In the first stage of design, the low velocity linac was assumed as a Wideröe type of which the parameters were decided based upon the experimental data at GSI [2] and at our institute [3]. It consists of two π-3π mode tanks and one π-π mode tank which accelerates the uranium ion in the energy range of 15 ∿ 146 Kev, 146 ∿ 305 Kev and 305 ∿ 1102 Kev, respectively. In Fig.1, the drawing of first π-3π mode linac is given and the basic characteristics of the tanks are given in Table 1. It was found that the effective shunt impedance of the Wideröe type structure were around 50 ∿ 60 MΩ/m in the specific energy region. In this structure, the power loss is mainly occurred at the drift tubes and stub lines and the loss at the stub line amounted to nearly the half of the total power loss.

In Table 2 the power loss at each part in the Wideröe type structure are given. This large power loss is inevitable due to the large current in the stub lines of which the short positions are adjusted to give an adequate gap voltage distributions in the array of drift tubes. It is true that the large diameter of the stub line can reduce the power loss in it, but it results in the more complicated structure and it would not be desirable.

Then we have studied other two types of low velocity structure, namely interdigital H structure and RF-Quadrupole linac, both of which are excited in TE mode.

3. Interdigital H Structure

The low velocity linac which is excited in TE_{11n} mode — Interdigital H structure have been studied by H. Morinaga, M. Brez et al, and J. potter [4, 5, 6] and it has been demonstrated that the structure has a large shunt impedance with a small diameter of the tank and a relative low RF frequency. At München University, the IH structure linac was constructed as a post accelerator of the Tandem Van de Graaff. They obtained a high shunt impedance of 120 ∿ 200 MΩ/m in the velocity region of β = 5 ∿ 10 %, but the drift tubes did not contain the focusing quadrupole magnet because it was served as a post accelerator with a relative large velocity. In order to study the feasibility of this structure in the low energy region, one-eighth scale model resonator is constructed (Fig.2) which is a π-π mode with a constant velocity and has a tank length of 1215 mm, a tank diameter of 150 mm and cell length of 22.5 mm (corresponding to β = 3.0 %). Two kinds of drift tubes are alternatively aligned in the tank axis, one is assumed to have a quadrupole magnet in it and has a diameter of 25 mm, and the other has a diameter of 14 mm without Q magnet. The resonator length can be varied by moving the short plate at the tank end. The n-th resonant frequency of TE_{11n} mode are plotted against n/ℓ where ℓ is a resonator length (Fig.3). It is clearly seen that the resonant frequency is dependent upon the value n/ℓ (not on the absolute value of ℓ) with a constant dimension of ridge.

These behaviours are well analyzed with a transmission-type equivalent-circuit-analysis which also well explains the field distribution in the gaps. On the basis of the above analysis, the effective shunt impedances Z_{eff} of IH structures are calculated. The results show that Z_{eff} is 54 ∿ 197 MΩ/m in the velocity region of β = 0.5 ∿ 1.4 % with a π-3π mode and it is around 150 MΩ/m in the region β = 1.4 ∿ 4 % in the π-π mode. They are two or three times larger than the measured values at the Wideröe linac.

Considering the simplicity of structure and the high shunt impedance, IH structure would be superior to the Wideröe structure. In the low energy region such as 15 Kev, however, Z_{eff} decreases to ∿ 50 MΩ/m which is nearly equal to the value obtained in the Wideröe structure.

4. RF-Q Linac

It was proposed by Kapchinskii and Teplyakev [7] that the four chamber resonator excited with TE_{21n} mode, has a action of acceleration and focusing by a quadrupole RF electric field and the structure is expected to exhibit very high capture efficiency (greater than 95 %) because it captures the beam adiabatically before the beam experiences much acceleration. It can accept the DC beam from the electrostatic accelerator and can make a bunched beam suitable for the following linear accelerator without any beam loss. Then it is a good interface between the DC accelerator and the usual drift tube type RF linac.

A one-eighth model cavity was made with a tank length of 1.0 m and a diameter of 18.8 cm. It has four vanes and interstitial vane at both ends of the tank. (Fig.4) The TE_{21n} and TE_{11n} modes interfere with each other at the large depth of vane (Fig.5-a) but the TE_{11n} mode can be completely suppressed by interstitial vane (Fig.5-b). The measurement of electric field shows the usefulness of RF Q type linac. The beam dynamics in the RF-Q structure is studied by computer-simulation and a typical result is given in Fig.6 where the ion is assumed as $^{238}U^{7+}$ and the injection energy is 15 Kev/u. The RF frequency is 50 MHz. The vane modulation is varied from 1.0 to 2.2 linearly along the cell number and the equilibrium phase is also varied linearly from - 90° to - 30°. It is shown that the U^{7+} can be accelerated from 15 Kev to 125 Kev with a tank length of 2.62 m and a vane potential of 300 KV. The bore diameter is 2.0 cm and the gap capacitance is experimentally measured at 40 pF/m. The shunt impedance is calculated at 60 MΩ/m where we must note that the definition of shunt impedance is different from the effective shunt impedance at IH or Wideröe structures because the equilibrium phase is varied in this structure.

Considering the quite simple structure of the resonator and high trapping efficiency of the beam, it can be concluded that the RF-Q structure is suitable for the initial part of the linac.

References

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Table 1 The injector linac specification.

	Wideröe 1	Wideröe 2	Wideröe 3	Alvarez 1	Alvarez 2
Operation Mode	π-3π, 38 gaps	π-3π, 20 gaps	π-π, 36 gaps	2π, 46 gaps	2π, 108 gaps
Synchrotron Phase (deg.)	-30.0	-30.0	-30.0	-25.84	-25.84
T/A (MeV/u)	0.015 - 0.146	0.146 - 0.305	0.305 - 1.102	1.102 - 1.603	1.600 - 10.023
v/c (%)	0.562 - 1.768	1.768 - 2.557	2.557 - 4.861	4.861 - 5.859	5.854 - 14.553
ϵ	0.0294 (U^{7+})	0.0294 (U^{7+})	0.0672 (U^{16+})	0.0672 (U^{16+})	0.193 (U^{46+})
L (m)	5.5	5.4	8.0	7.5	32.1
$\Delta T/(L\cdot\epsilon)$ (MeV/m)	0.85	1.00	1.49	0.988	1.36
Z_{eff} (MΩ/m)	67.8	36.0	47.6	41.8 - 43.4	43.3 - 31.6
Power Loss (MW)	0.076	0.215	0.494	0.206	1.903
Q-magnet Sequence	FDFD	FDFD	FFDD	FFDD	FFDD
G (kG/cm)	10.0 - 3.18	3.18 - 2.20	3.50 - 1.83	4.00 - 3.30	3.30 - 1.33
$\cos\mu$	0.849	0.849	0.572	0.906	0.906
Aperture (mmϕ)	20, 25, 30	30	35	40	40
Admittance (mm mrad)	114 π	88.7 π	127 π	248 π	203 π

Table 2 The power dissipation of each Wideröe tank*.

	Tank 1	Tank 2	Tank 3
All drift tube and stems	13.6 kW	20.7 kW	116.6 kW
Drift tube line	7.8	11.9	67.8
Tank wall	1.0	1.6	9.0
Stub line inner conductor	23.8	90.9	124.5
Stub line shorting plungers	4.6	11.6	28.1
Stub line outer conductor	7.4	28.4	34.2
Total power dissipation	58.2	165.2	380.2
Including joint losses	75.6	214.7	494.3

* Duty factor 100 %

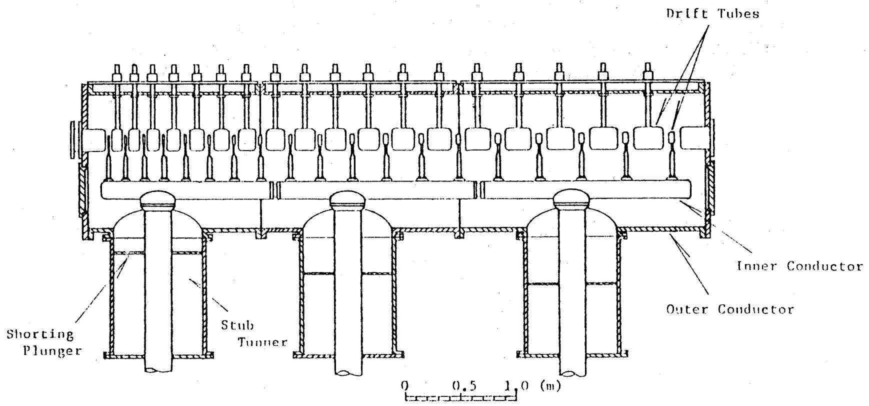

Fig. 1 π-3π mode Wideröe linac

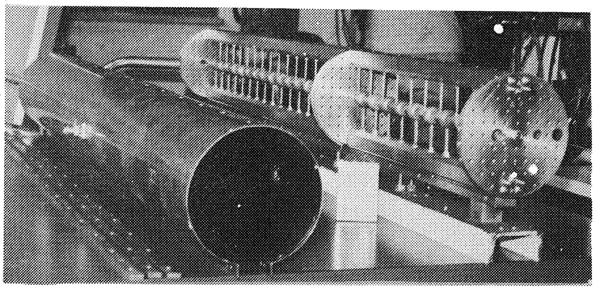

Fig. 2 1/8 scale model of IH structure

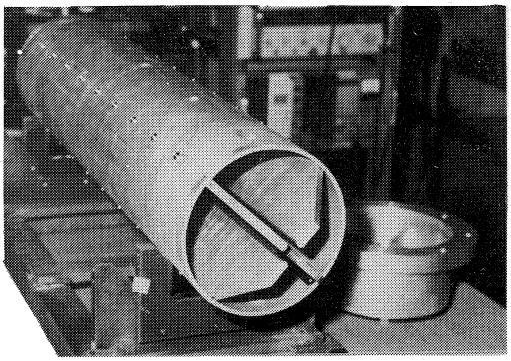

Fig. 4 RF-Q structure

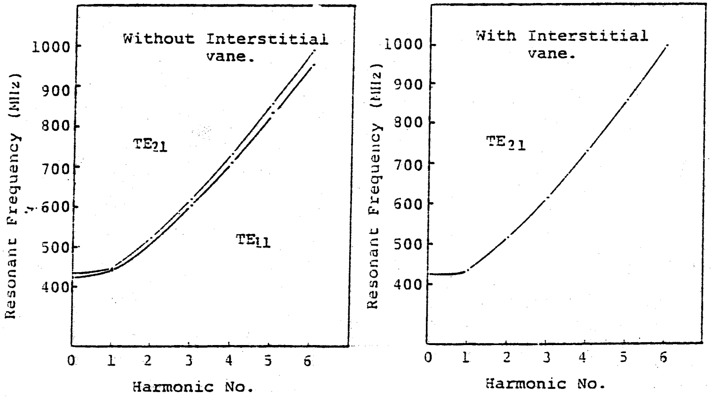

Fig. 5 Dispersion curves of RF-Q model linac with and without interstitial va

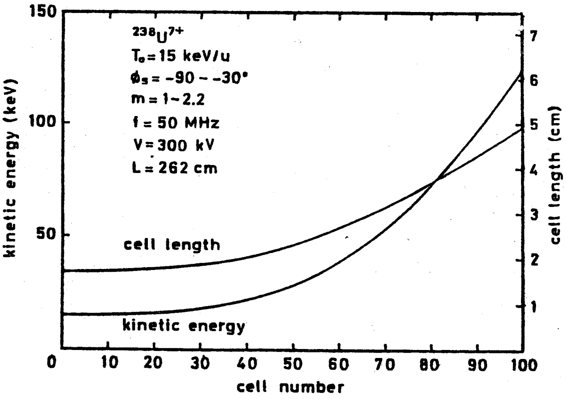

Fig. 6 Beam dynamics in the RF-Q structure